

# Current experimental results in neutrino-nucleus scattering

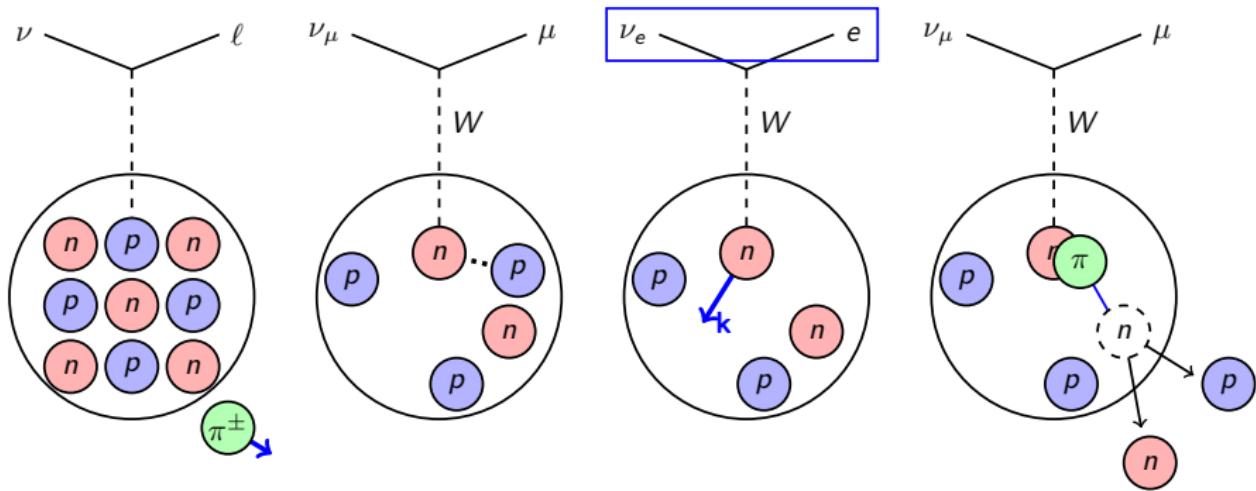
Philip Rodrigues

University of Rochester

February 5, 2015

## Outline

- ▶ What we're measuring and how we're measuring it
- ▶ Four physics topics:



1. Coherent charged pion production
2. Probes of multinucleon interactions
3. Electron neutrino scattering
4. (Incoherent) pion production as a probe of FSI

What exactly *are* we measuring, and how are we measuring it?

## Experiments are moving towards defining processes by final-state particles

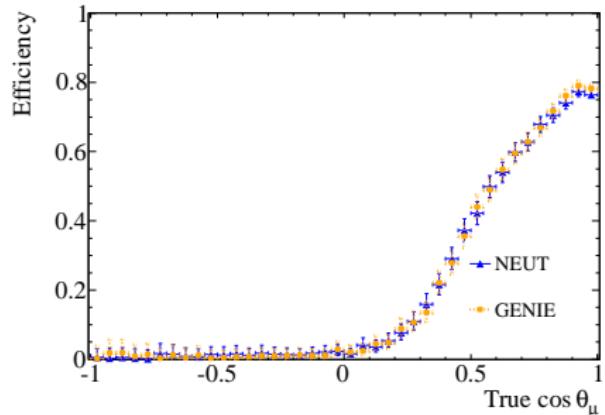
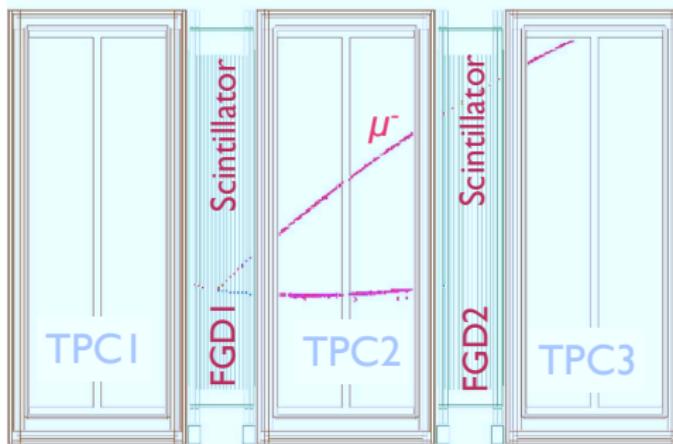
able in a Čerenkov-style detector. The understanding of FSI effects is model-dependent, with large uncertainties on the FSI cross sections. An “observable” interaction is therefore defined by the leptons and mesons that remain after FSI effects. Observable interactions are also inclusive of all nucleon final states. To reduce the FSI-model dependence of the measurements reported here, the signal is defined as a  $\mu^-$  and a single  $\pi^0$  that exits the target nucleus, with any number of nucleons, and with no additional mesons or leptons surviving the nucleus. This is referred to as an observable  $CC\pi^0$  event. The results presented here are not corrected for nuclear effects and intra-nuclear interactions.

PRD 83, 052009

Detector acceptance can define a limited phase space for the measurement

T2K ND280

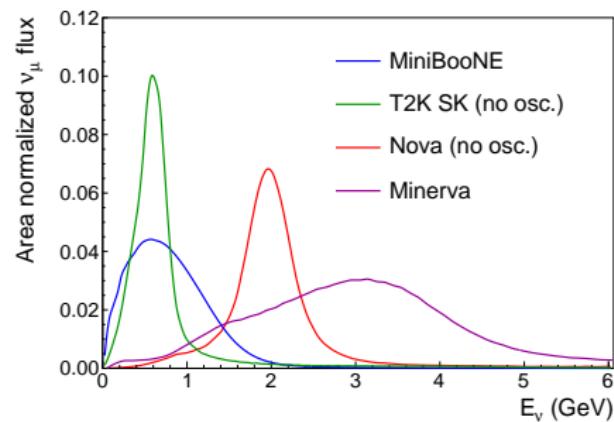
Run #: 4200 Evt #: 24083 Time: Sun 2010-03-21 22:33:25 JST



PRD 87, 092003

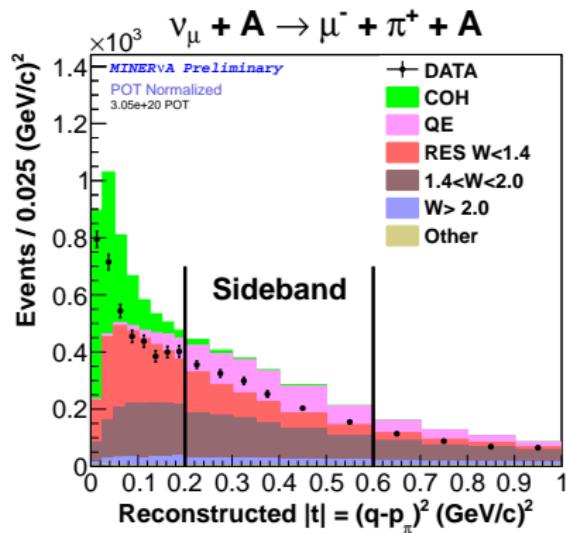
- ▶ (Plus similar issues in MINER $\nu$ A)

Measurements are often experiment-dependent because of flux and target type

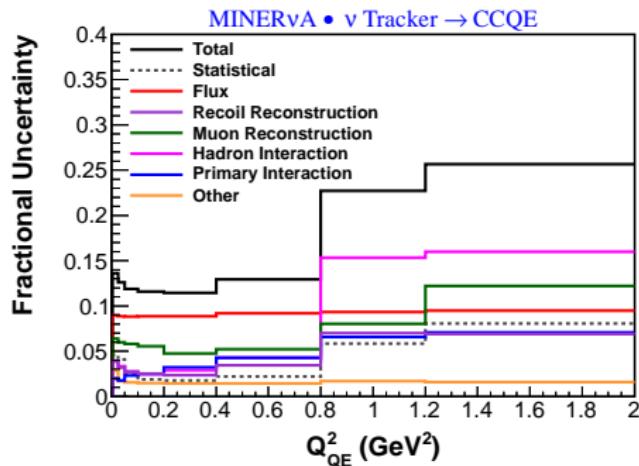
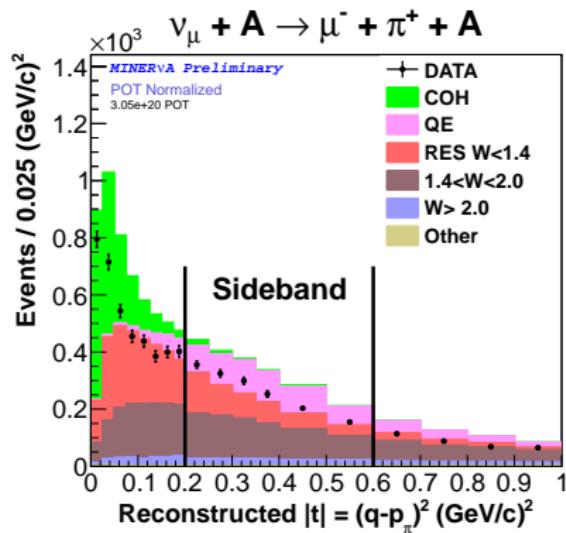


Experiment	Target(s)
MINER $\nu$ A	CH, C, Fe, Pb
MiniBooNE	CH <sub>2</sub>
T2K ND280	CH
K2K	CH (H <sub>2</sub> O)
SciBooNE	CH
ArgoNeuT	Ar

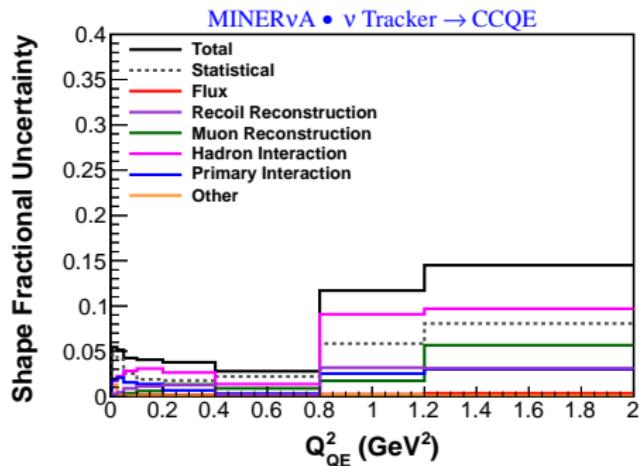
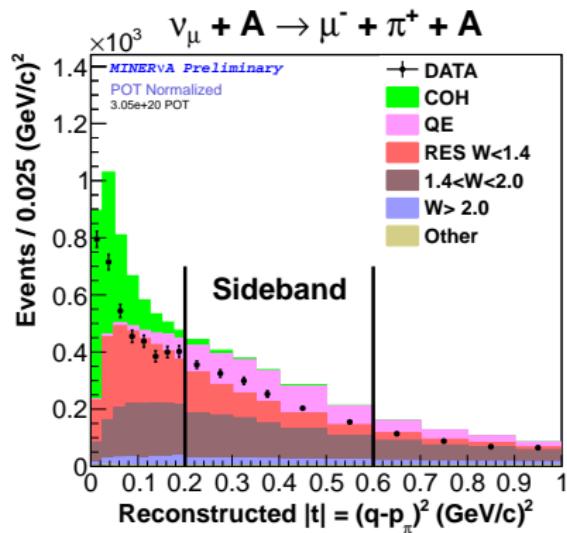
Background constraints and shape-only comparisons are important technology for measurements and interpretation



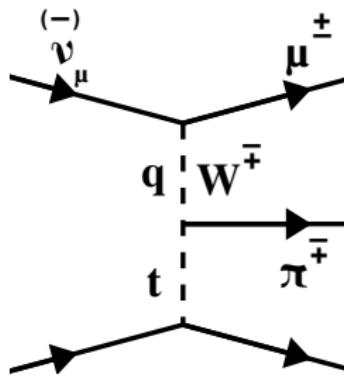
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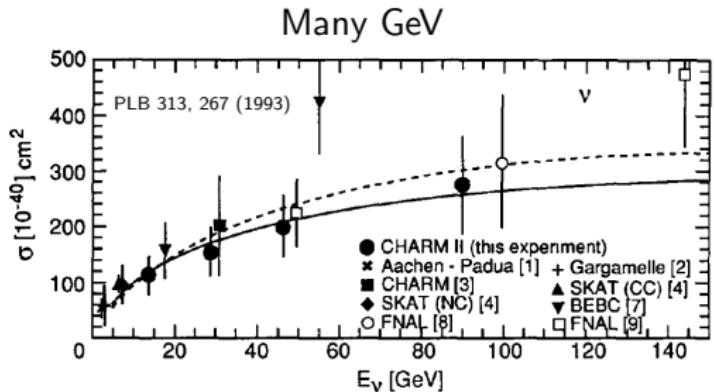
Background constraints and shape-only comparisons are important technology for measurements and interpretation



Towards a coherent coherent pion story?

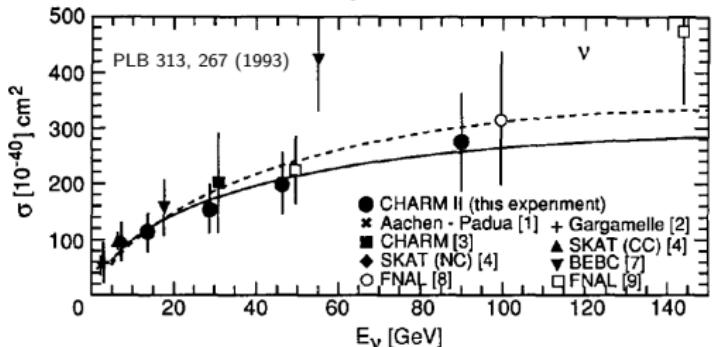


# CC coherent $\pi^\pm$ production observed at high, but not low, energies



# CC coherent $\pi^\pm$ production observed at high, but not low, energies

Many GeV

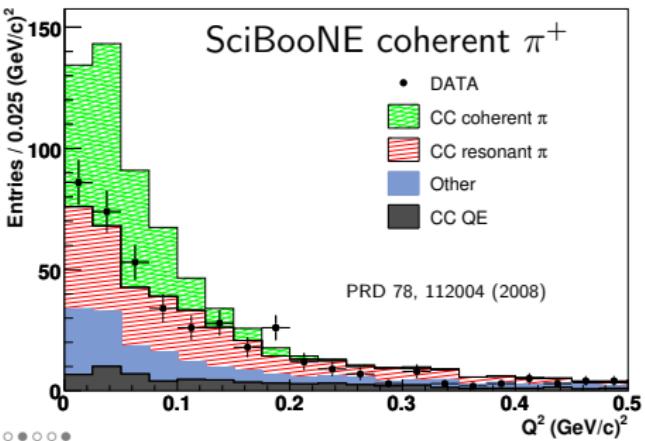


$\sim$  GeV

SciBooNE coherent  $\pi^+$

- DATA
- CC coherent  $\pi$
- CC resonant  $\pi$
- Other
- CC QE

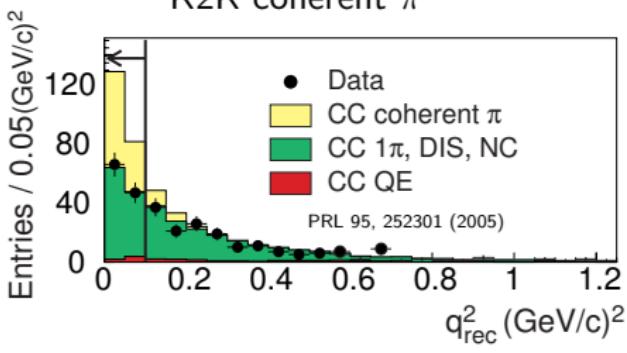
PRD 78, 112004 (2008)



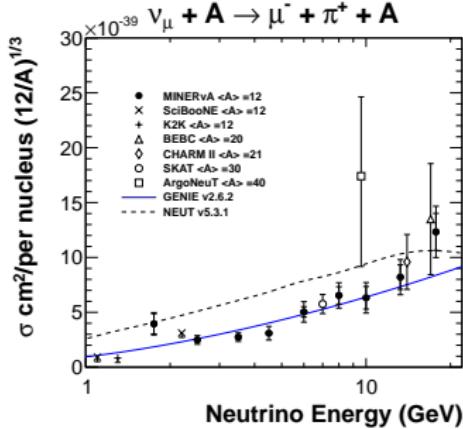
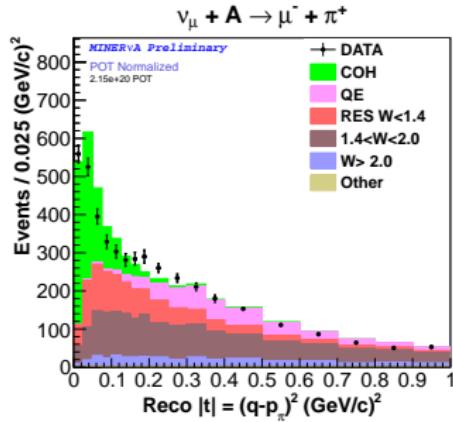
K2K coherent  $\pi^+$

- Data
- CC coherent  $\pi$
- CC 1 $\pi$ , DIS, NC
- CC QE

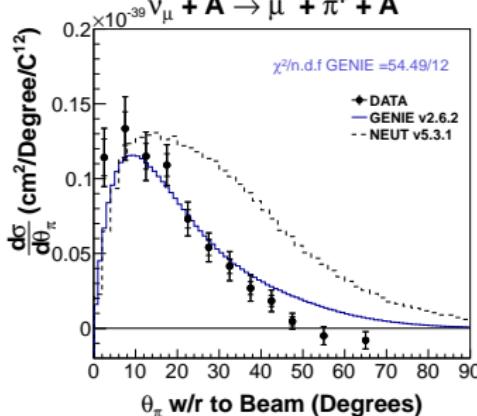
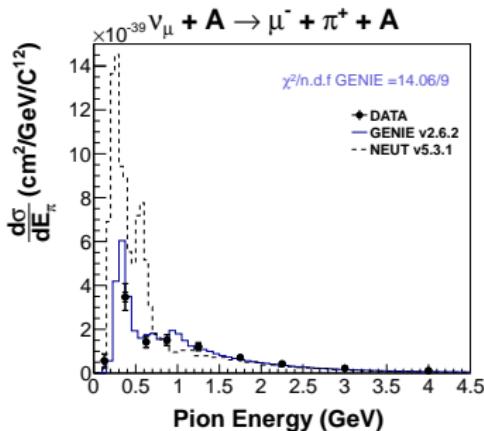
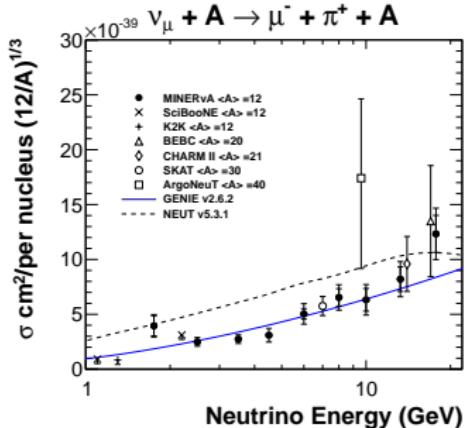
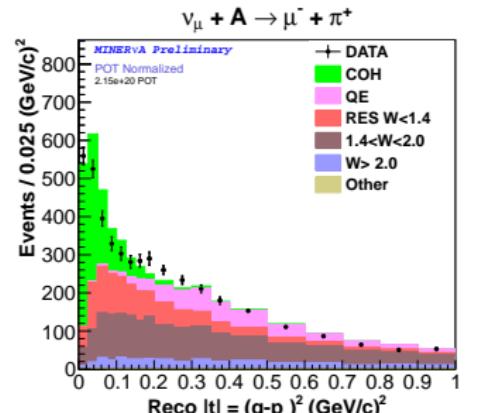
PRL 95, 252301 (2005)



# MINER $\nu$ A sees clear evidence for coherent pion production

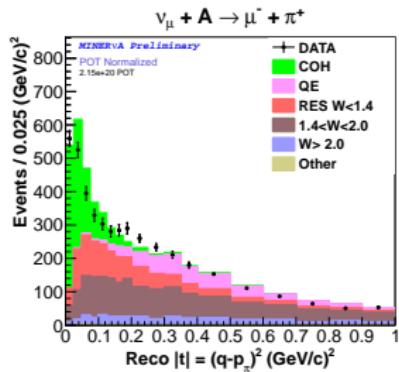
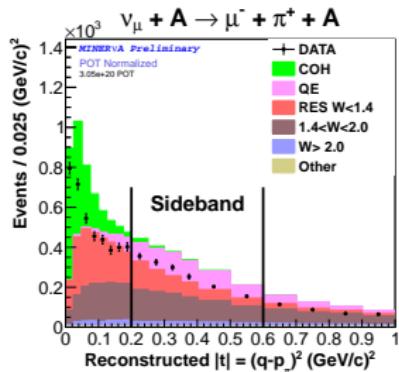


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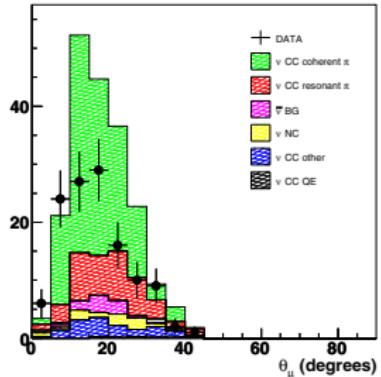
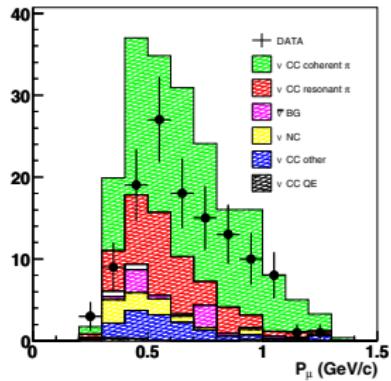


Difficulties in modeling the signal and background processes might explain the discrepancy

### MINER $\nu$ A background tuning

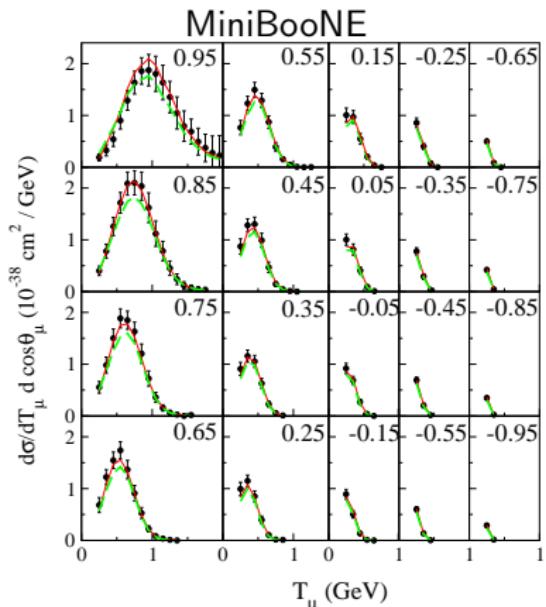


### SciBooNE $\theta_\pi < 35^\circ$ (arXiv:0909.5127)

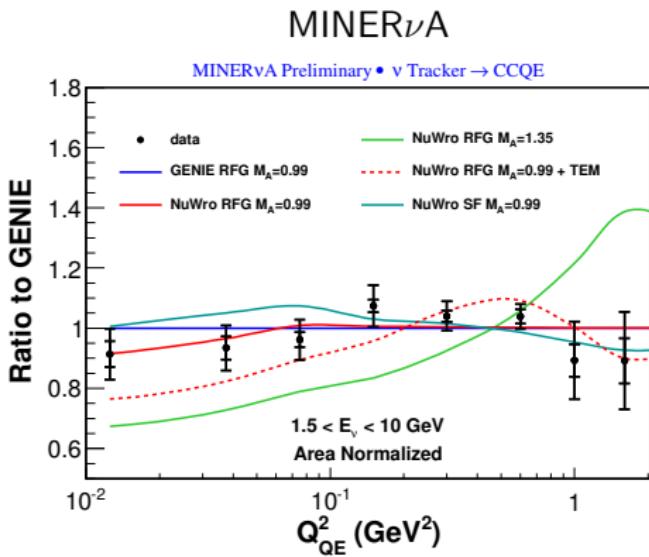


## Probes of multinucleon interactions

MiniBooNE and MINER $\nu$ A  $\nu_\mu$  CCQE, taken together, prefer models incorporating multinucleon effects



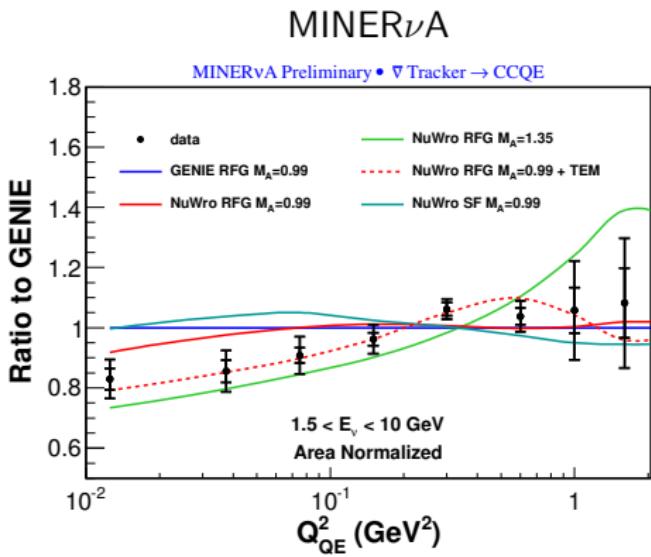
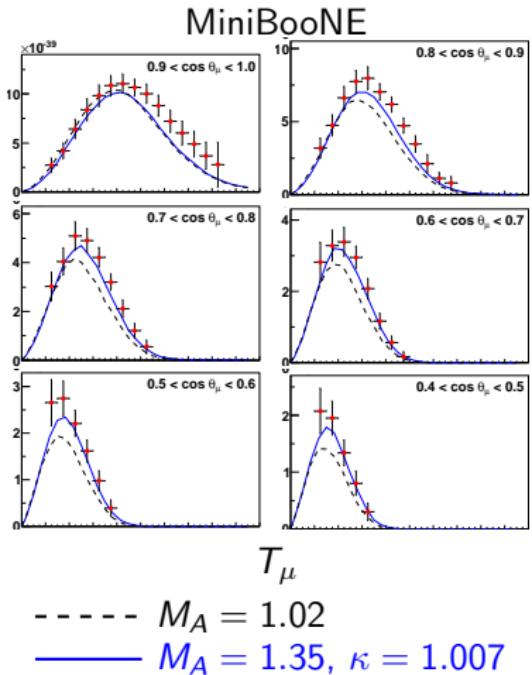
— RFG,  $M_A = 1.3$   
 - - -  $npnh + RPA + M_A = 1.05$



PRL 111, 022502

Data: PRD 81, 092005. Model: Nieves *et al.*, arXiv:1110.1200

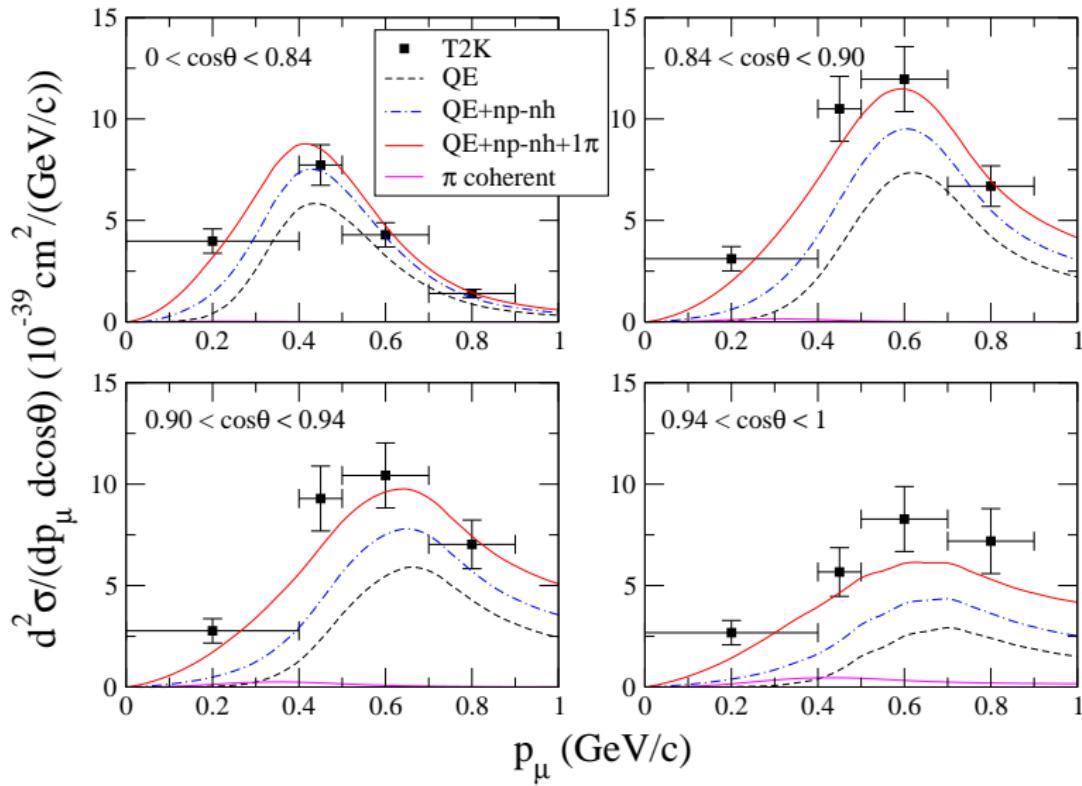
A similar picture is seen in  $\bar{\nu}_\mu$  CCQE



PRL 111, 022501

PRD 88, 032001

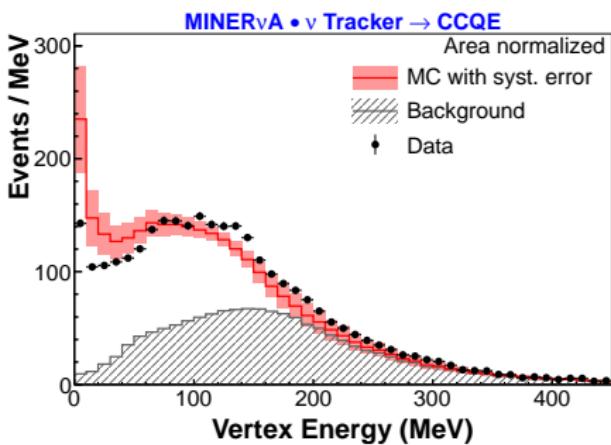
# T2K's ND280's double-differential $\nu_\mu$ CC inclusive measurement fits better to a model with multinucleon effects



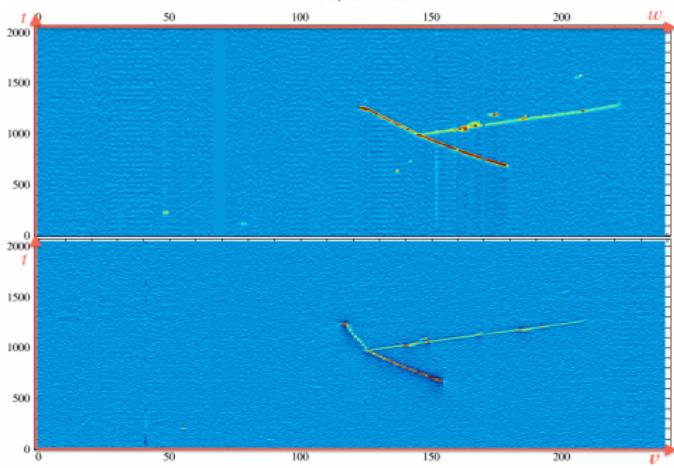
Data: PRD 87, 092003. Models: Martini and Ericson, PRC 90, 025501

MINER $\nu$ A and ArgoNeuT results suggest we can see effects of protons emitted from multinucleon interactions

MINER $\nu$ A  $\nu_\mu$  CCQE vertex energy

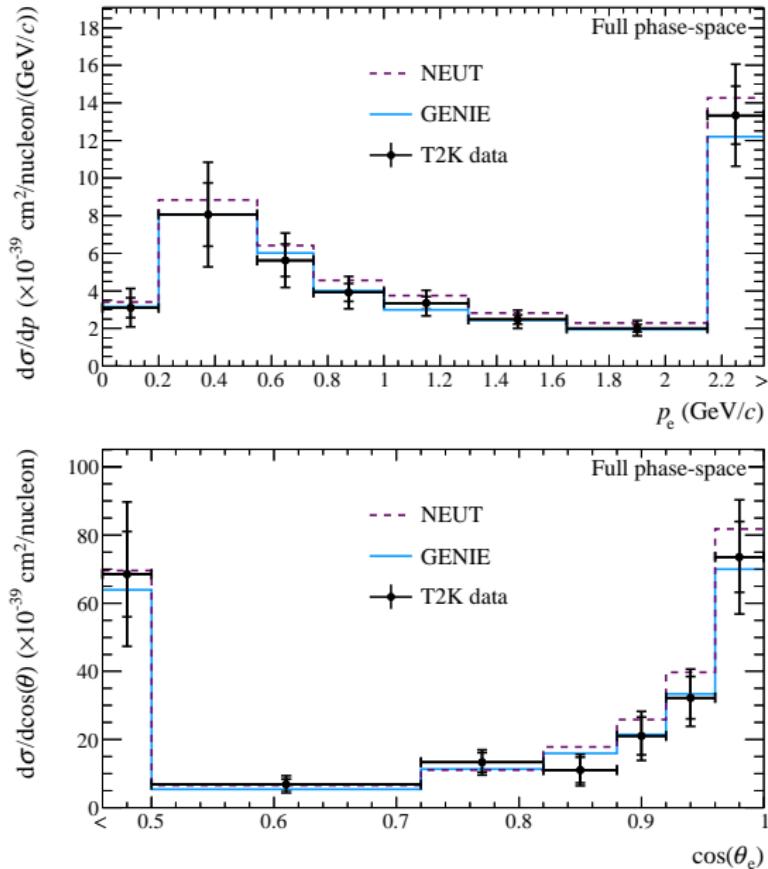


ArgoNeuT  
PRD 90, 012008

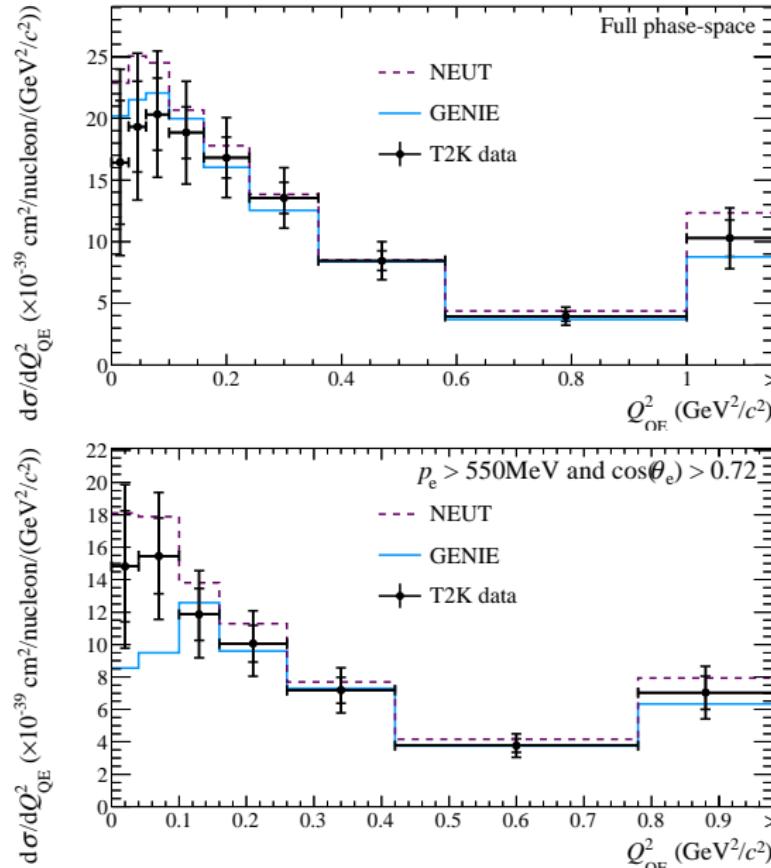


## Electron neutrino scattering

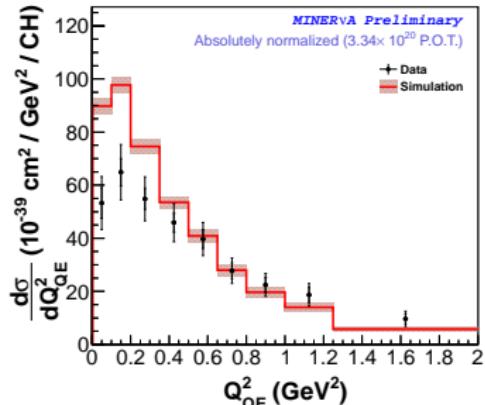
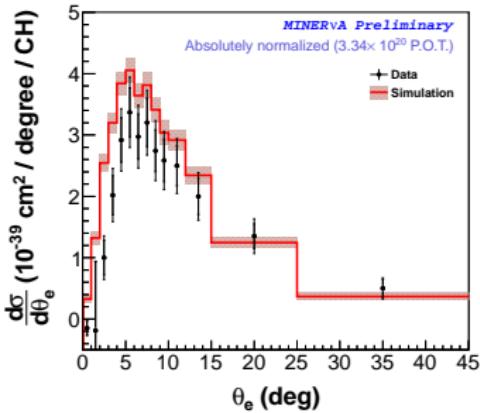
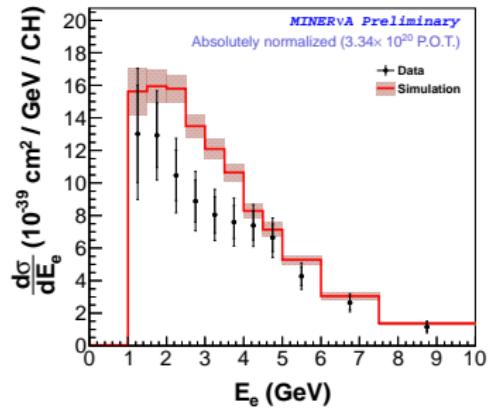
# The T2K ND280 $\nu_e$ CC inclusive measurement hints at low- $Q^2$ discrepancies with models (PRL 113, 241803)



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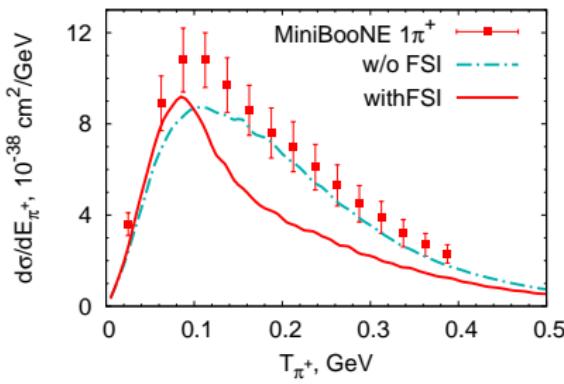
# A preliminary MINER $\nu$ A $\nu_e$ CCQE measurement suggests even larger discrepancies



Incoherent pion production as a probe of FSI

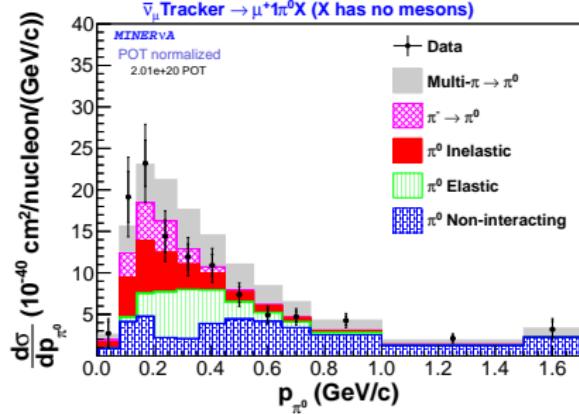
"Final state interactions" have a large effect on observed particle identity and kinematics

GiBUU MiniBooNE CC1 $\pi^+$



arXiv:1107.5947

MINER $\nu$ A CC1 $\pi^0$

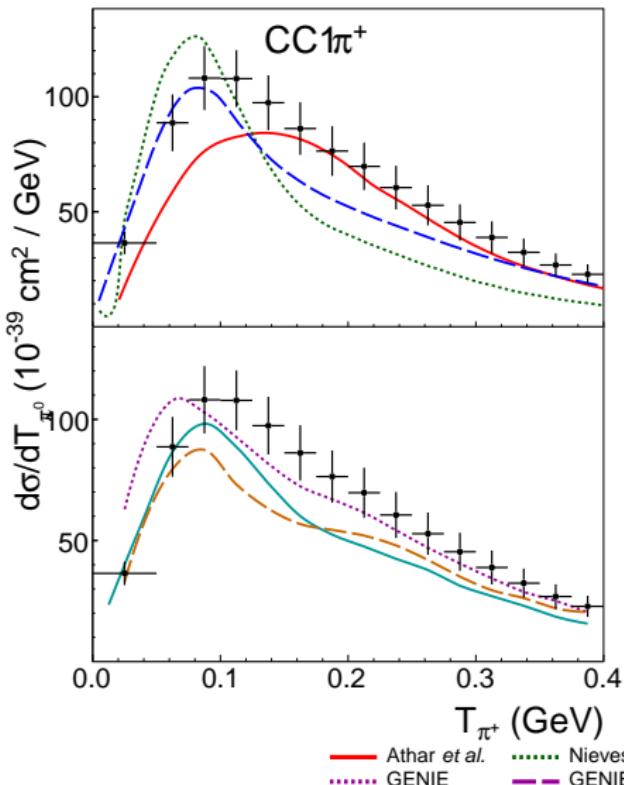


T. Le, Fermilab JETP seminar, Jan 9, 2015

# Some apparent tension between MiniBooNE and MINER $\nu$ A CC single $\pi^+$ production measurements...

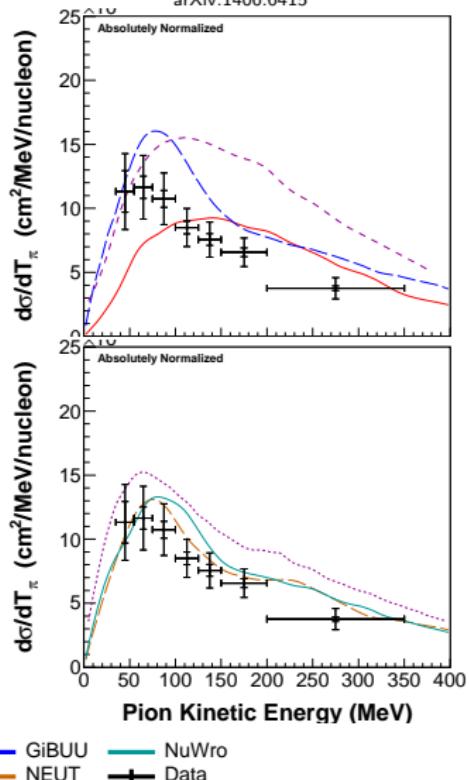
MiniBooNE

Data: PRD 83, 052007. Models: arXiv:1402.4709



MINER $\nu$ A

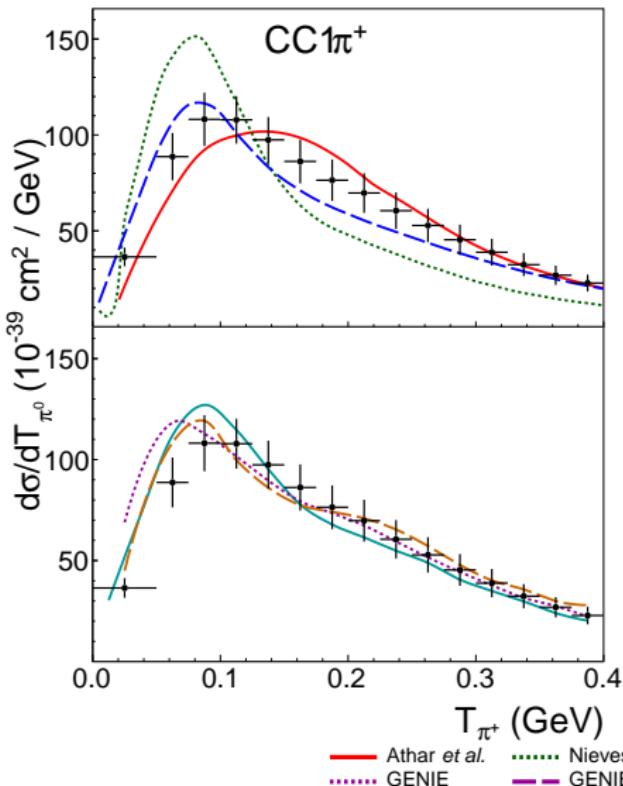
arXiv:1406.6415



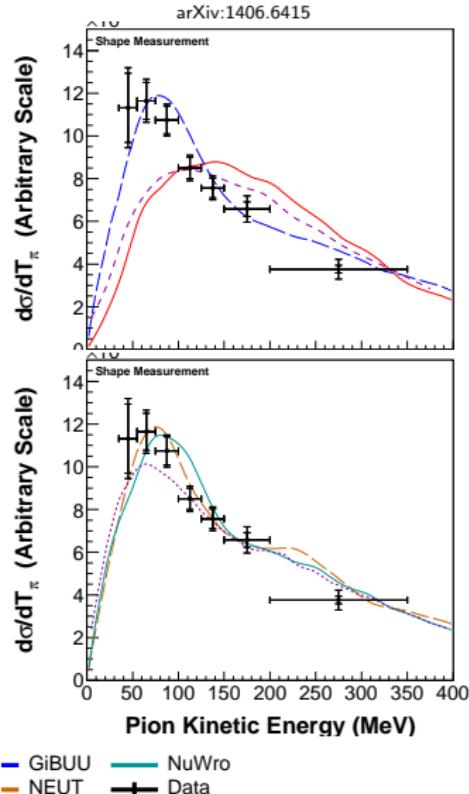
# Some apparent tension between MiniBooNE and MINER $\nu$ A CC single $\pi^+$ production measurements... but less in shape-only

MiniBooNE

Data: PRD 83, 052007. Models: arXiv:1402.4709



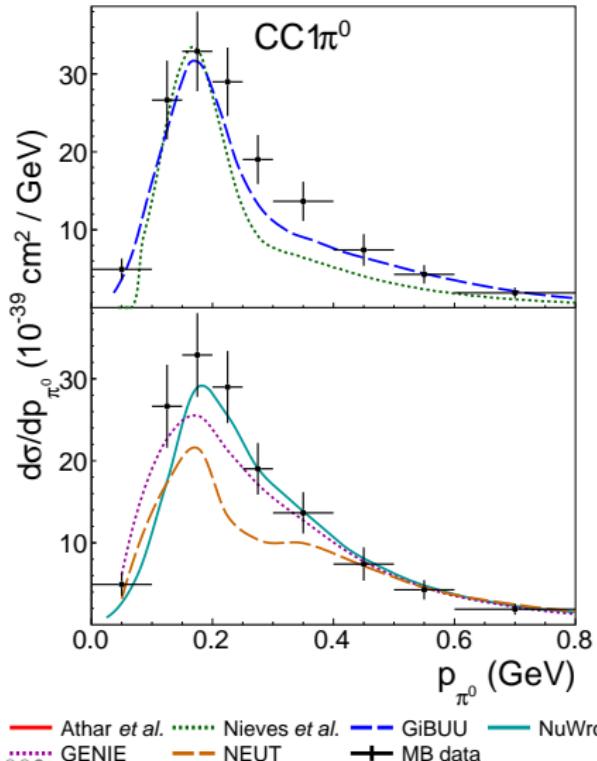
MINER $\nu$ A  
arXiv:1406.6415



Also some tension in MiniBooNE, MINER $\nu$ A  $\bar{\nu}_\mu$  ( $\bar{\nu}_\mu$ ) CC single  $\pi^0$  production...

### MiniBooNE $\nu_\mu$

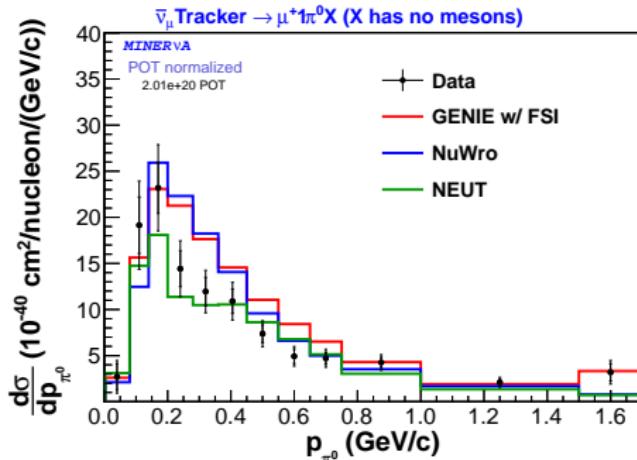
Data: PRD 83, 052009. Models: arXiv:1402.4709



► Apples to anti-apples comparison!

### MINER $\nu$ A $\bar{\nu}_\mu$

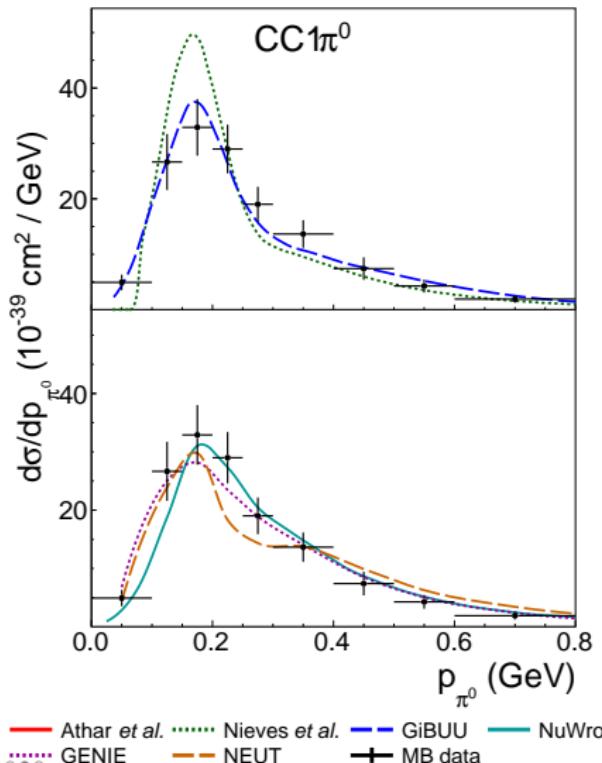
T. Le, Fermilab JETP seminar, Jan 9, 2015



Also some tension in MiniBooNE, MINER $\nu$ A  $\bar{\nu}_\mu$  ( $\bar{\nu}_\mu$ ) CC single  $\pi^0$  production... same in shape?

### MiniBooNE $\nu_\mu$

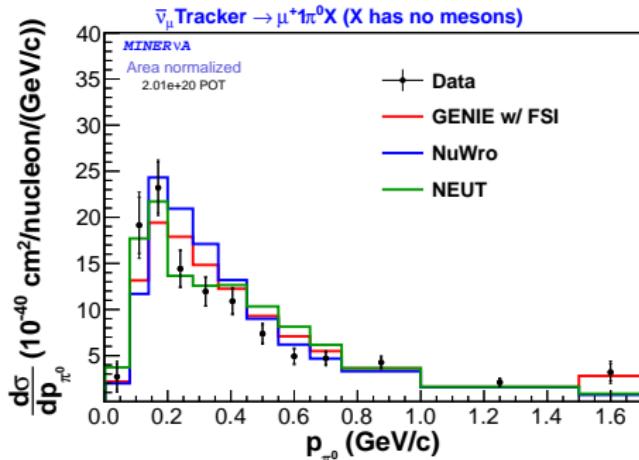
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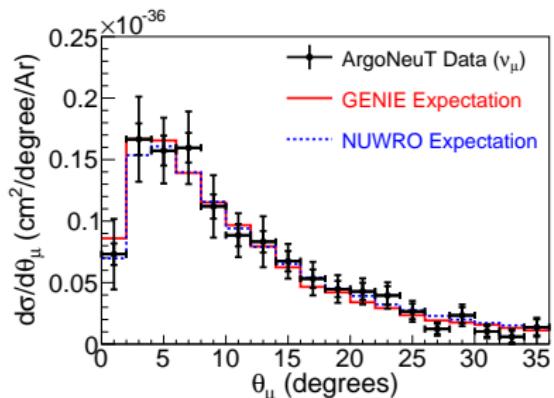
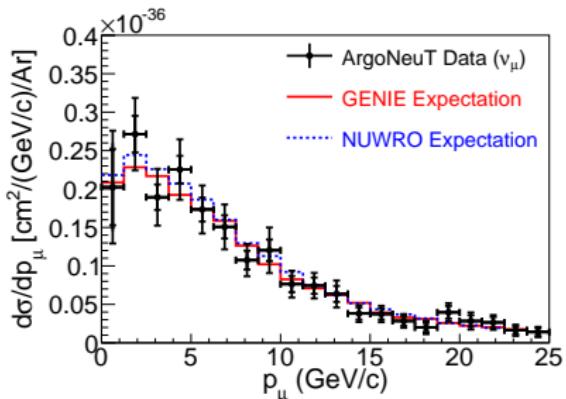
### MINER $\nu$ A $\bar{\nu}_\mu$

T. Le, Fermilab JETP seminar, Jan 9, 2015



# Special one-time only bonus slide: carbon is not the only nucleus

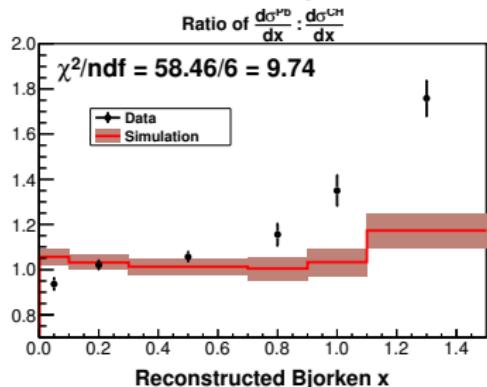
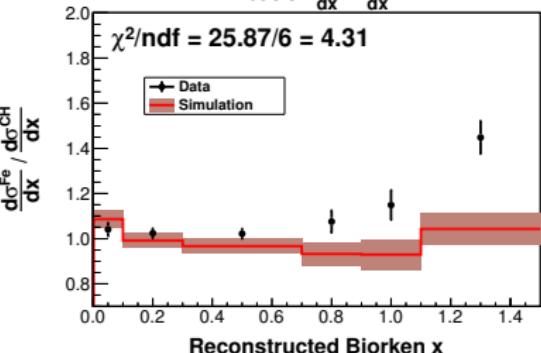
ArgoNeuT  
PRD 89, 112003



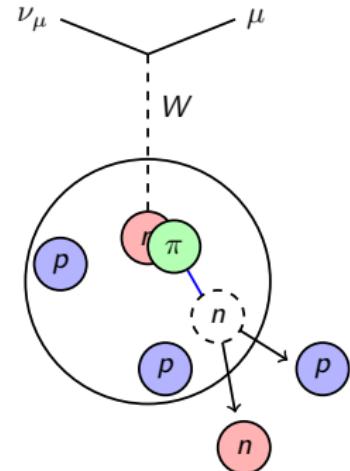
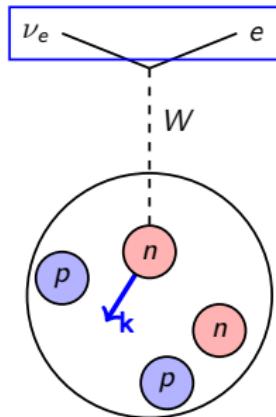
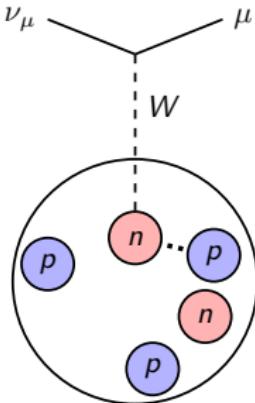
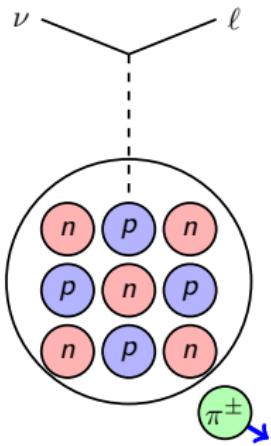
MINER $\nu$ A

PRL 112, 231801

Ratio of  $\frac{d\sigma_{Fe}}{dx} : \frac{d\sigma_{CH}}{dx}$

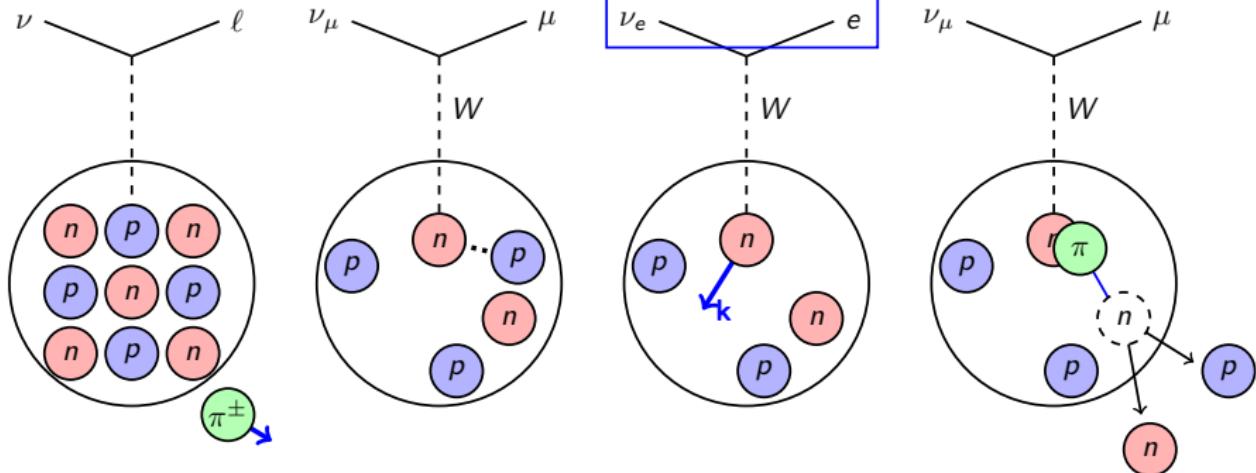


## Recap



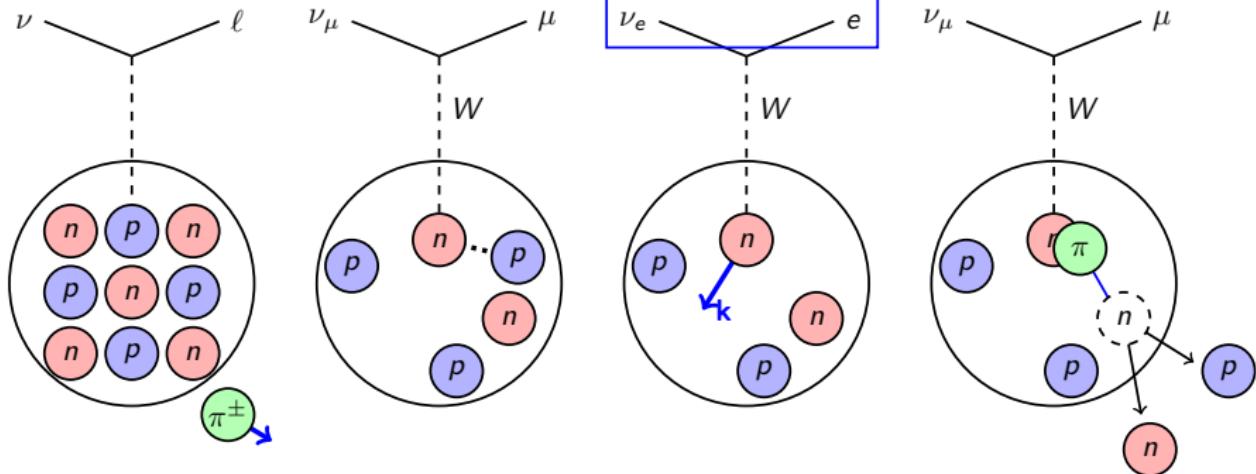
1. MINER $\nu$ A data, and a closer look at event kinematics, are clarifying coherent pion production around 1 GeV

## Recap



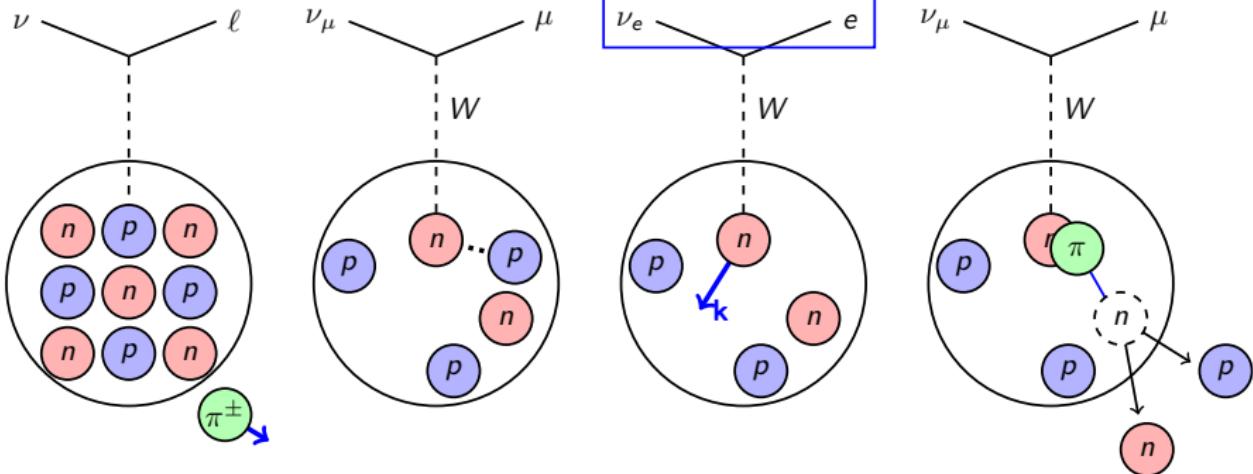
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2. Multinucleon effects are in the data and the models for  $\nu_\mu$  CCQE

## Recap



1. MINER $\nu$ A data, and a closer look at event kinematics, are clarifying coherent pion production around 1 GeV
2. Multinucleon effects are in the data and the models for  $\nu_\mu$  CCQE
3. Electron neutrino scattering measurements suggest generators are missing something

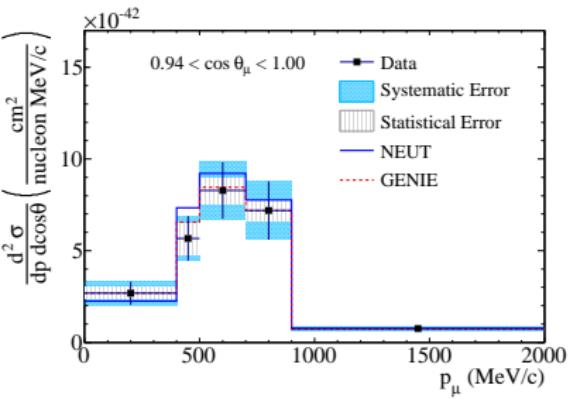
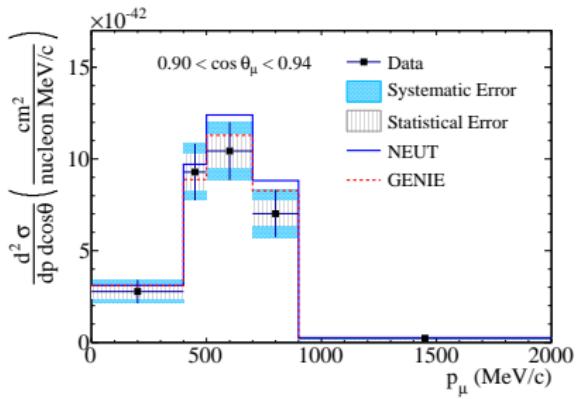
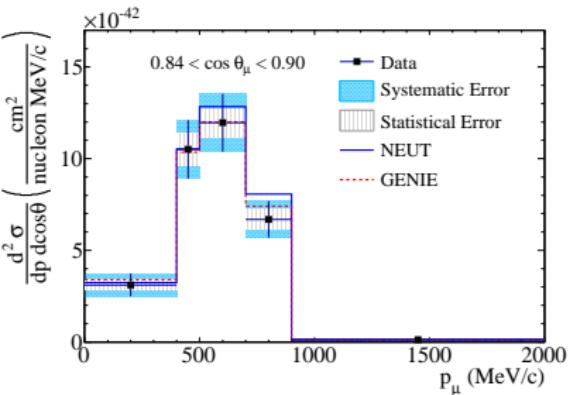
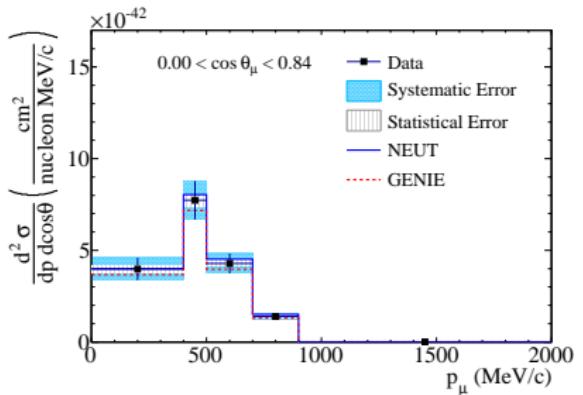
## Recap



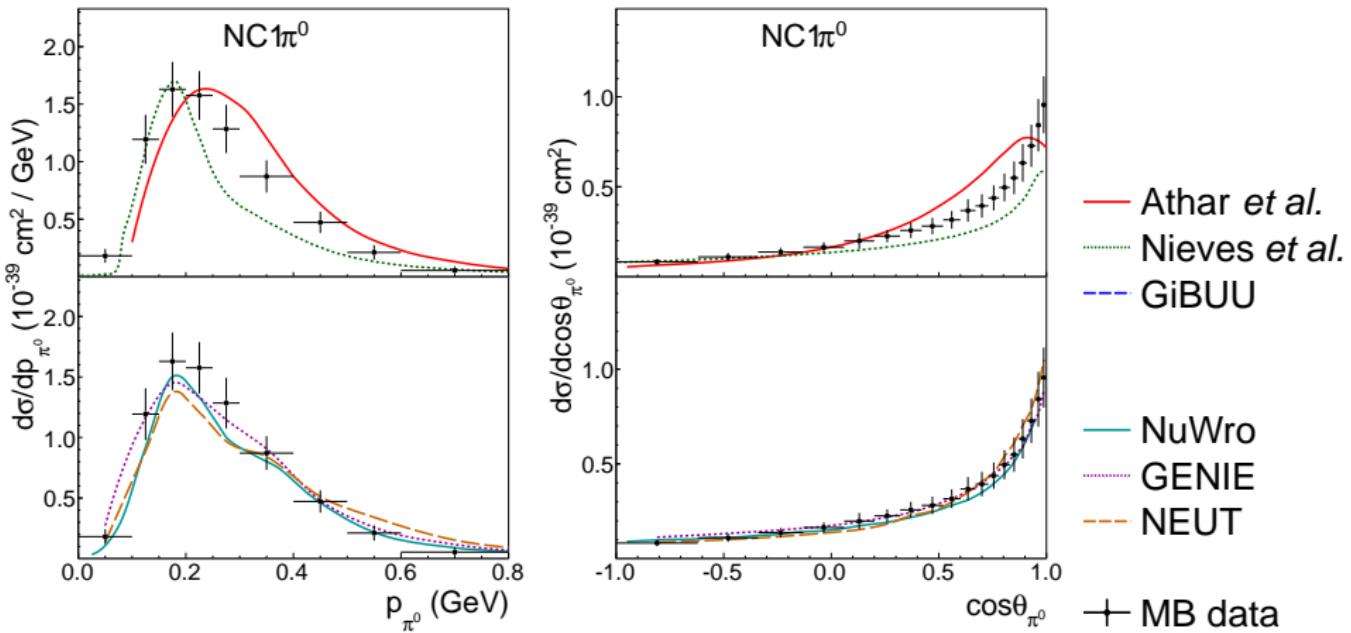
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2. Multinucleon effects are in the data and the models for  $\nu_\mu$  CCQE
3. Electron neutrino scattering measurements suggest generators are missing something
4. Pion production measurements suggest generator FSI models are sort-of OK

# Backup slides

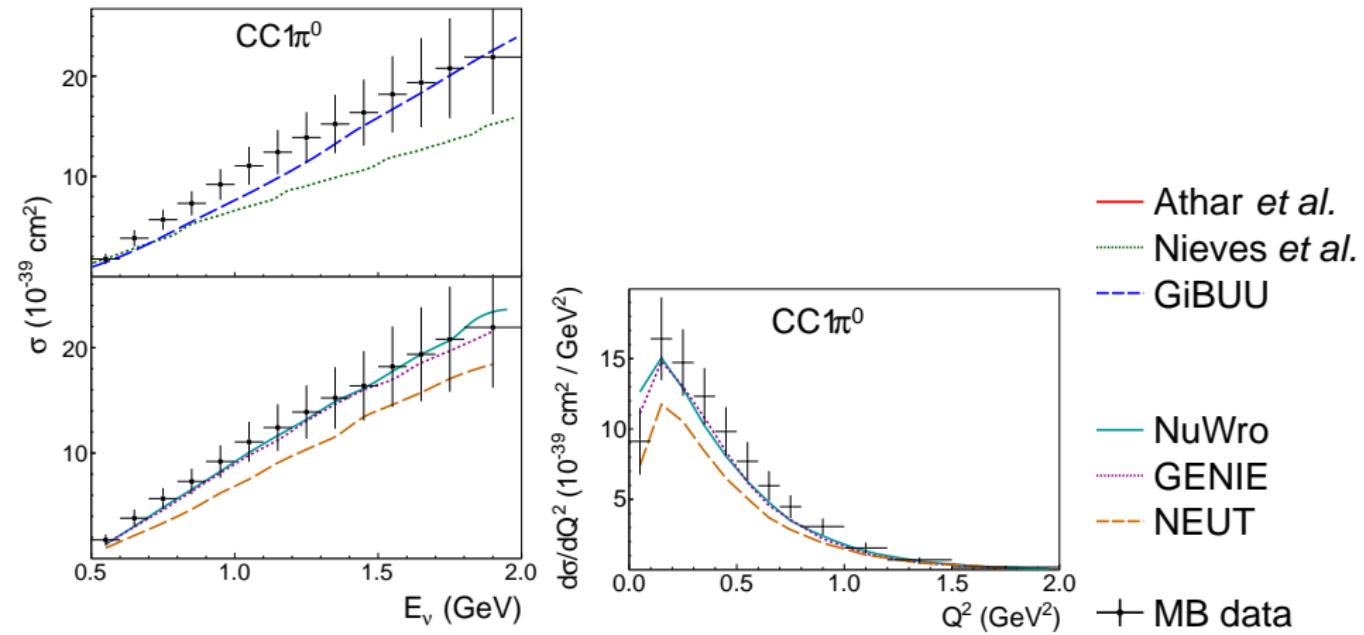
# T2K ND280 $\nu_\mu$ CC inclusive double-differential



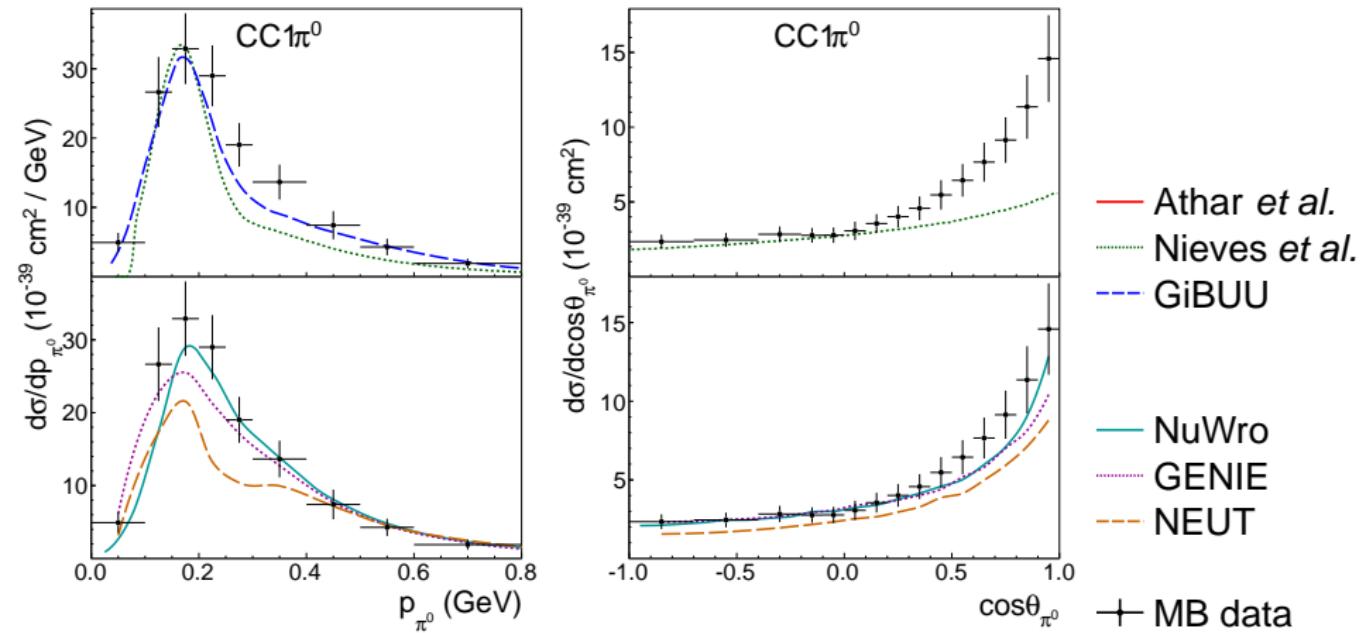
# MiniBooNE NC1 $\pi^0$ comparisons

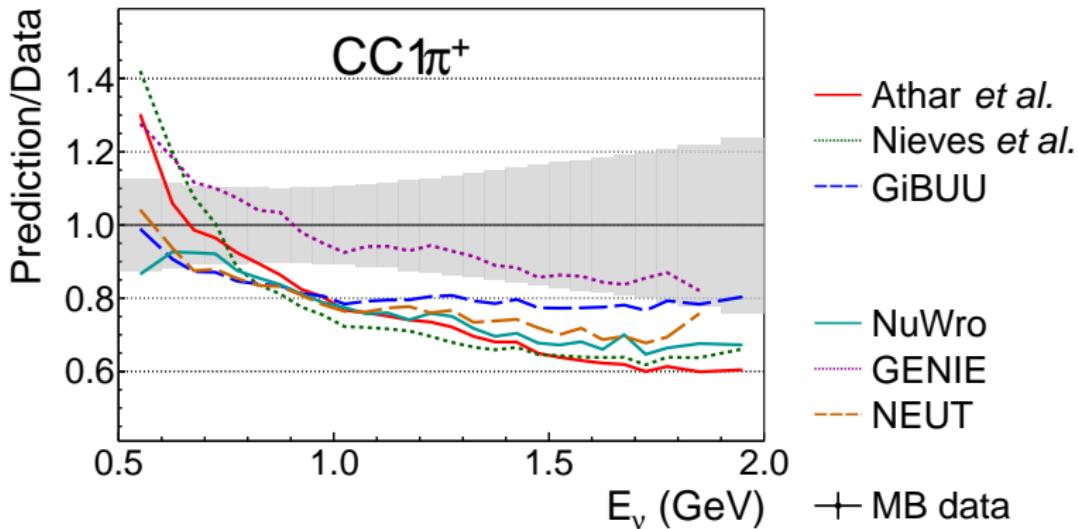


# MiniBooNE CC1 $\pi^0$ comparisons 1

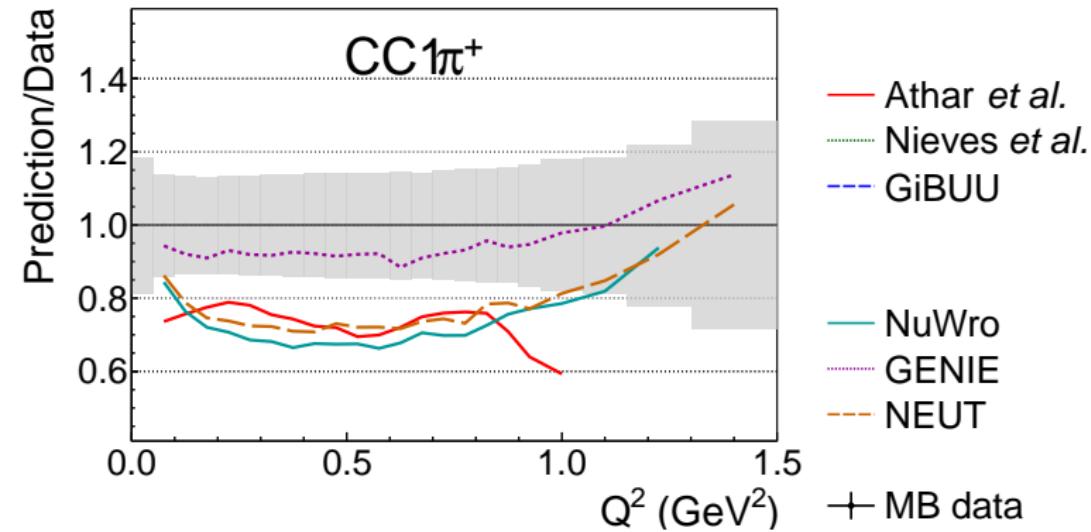


## MiniBooNE CC1 $\pi^0$ comparisons 2

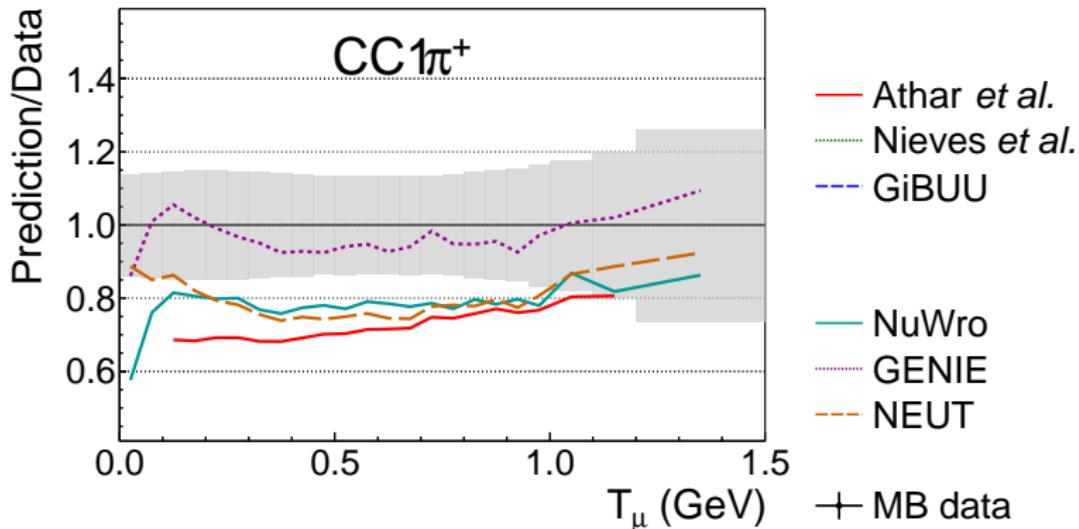




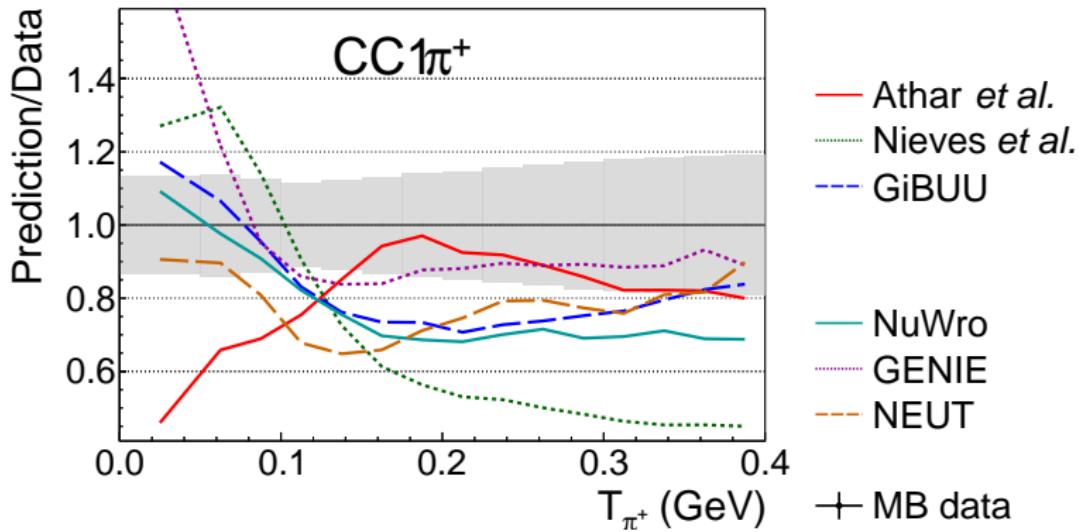
## ccpip-q2-ratios



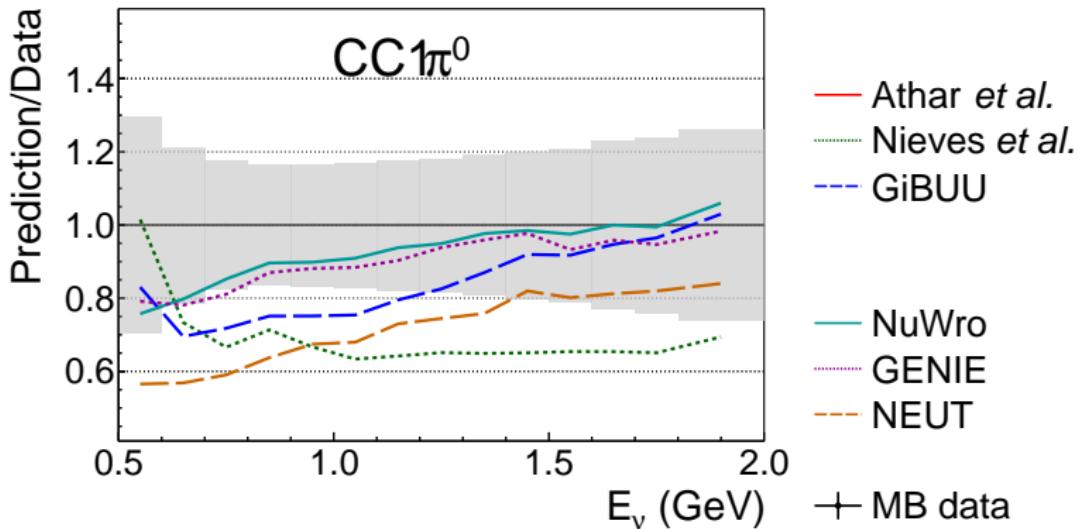
## ccpip-tmu-ratios



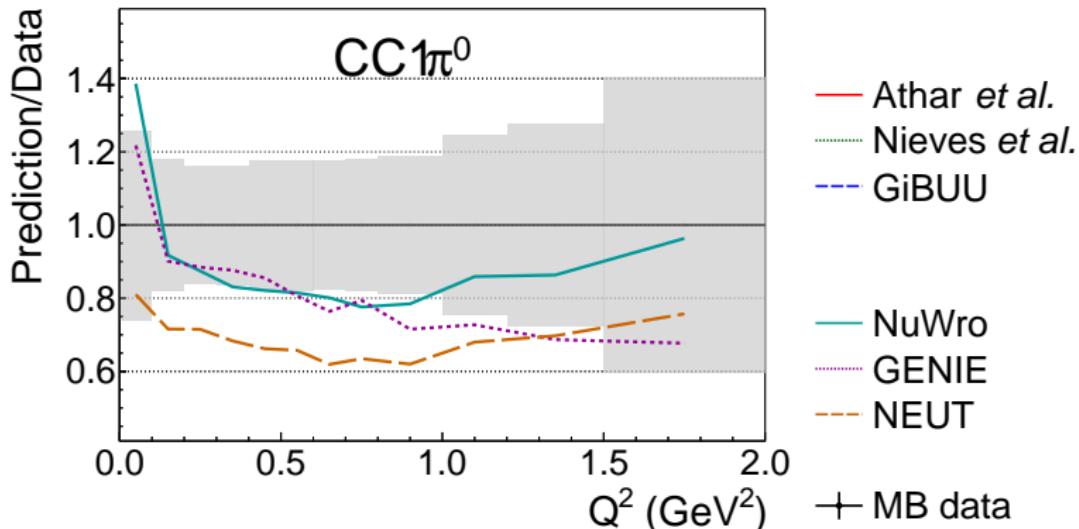
## ccpip-tpi-ratios



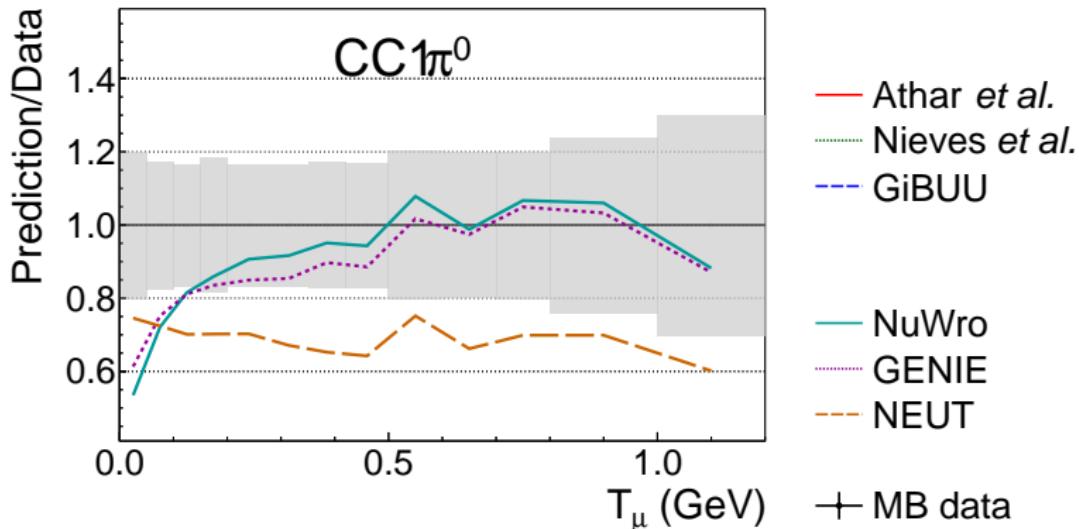
## ccpi0-enu-ratios



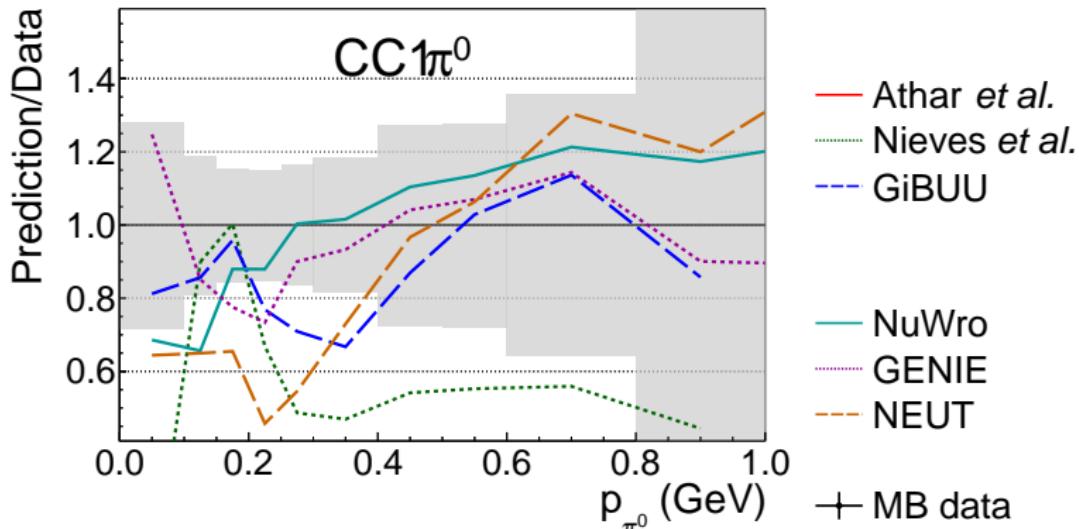
## ccpi0-q2-ratios



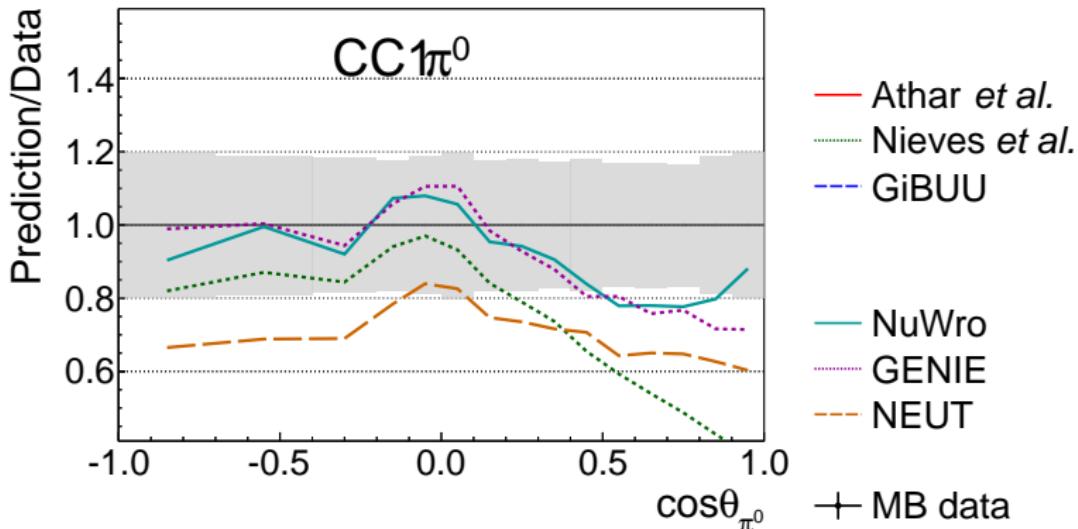
## ccpi0-tmu-ratios



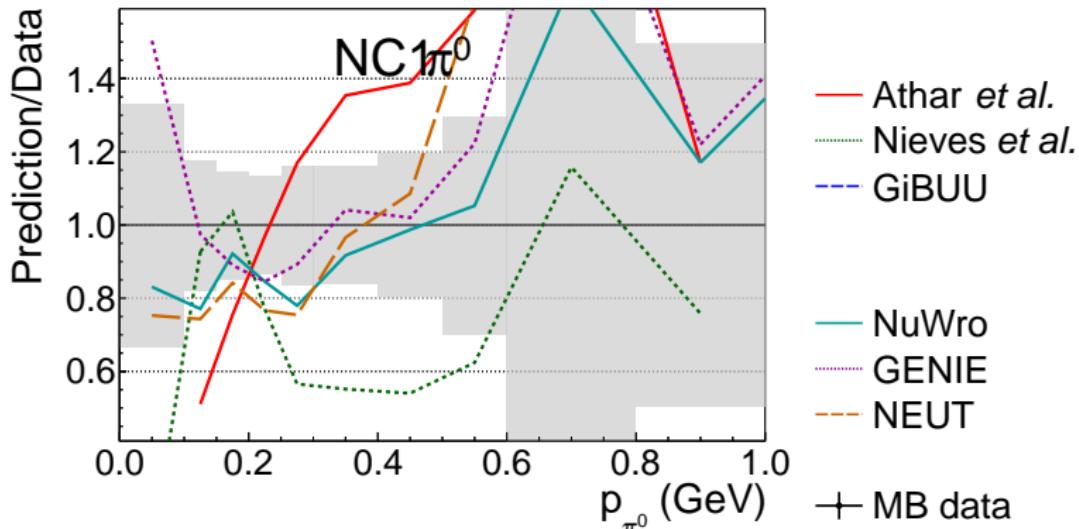
## ccpi0-ppi-ratios



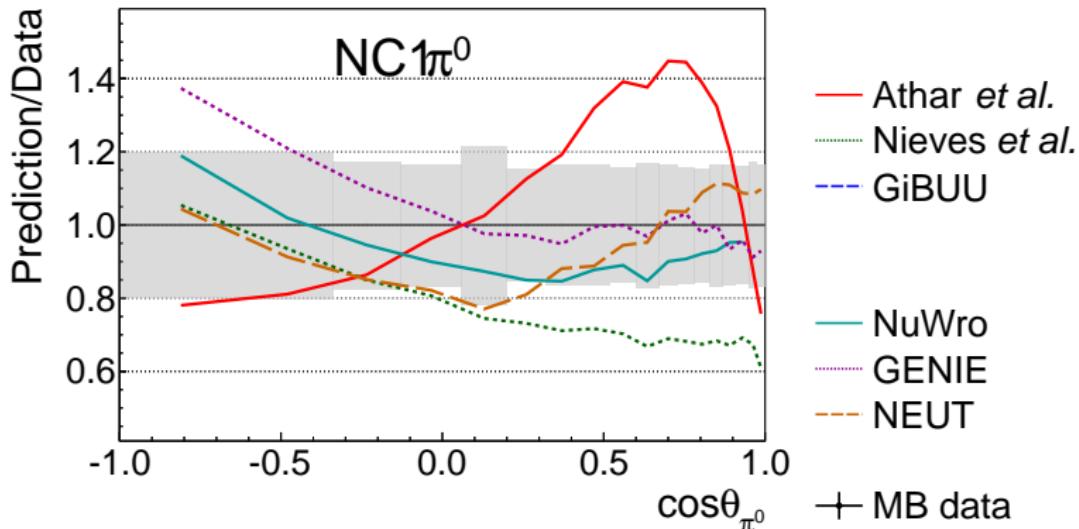
## ccpi0-cspi-ratios



## ncpi0-ppi-ratios

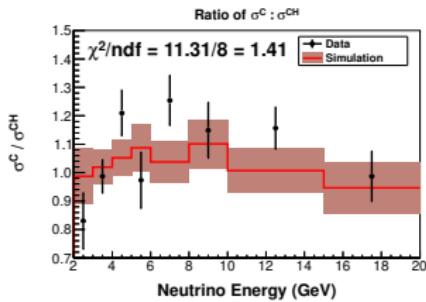


## ncpi0-cspi-ratios

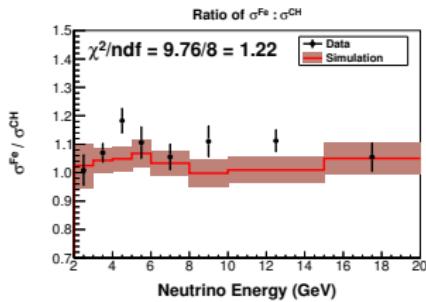


# MINER $\nu$ A passive target data shows consistency with model in $E_\nu$ , but not $x$

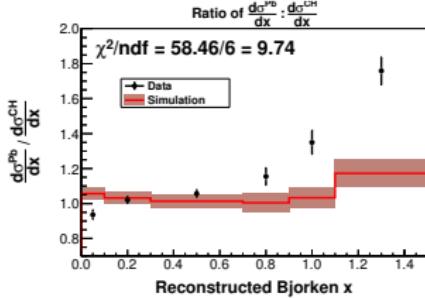
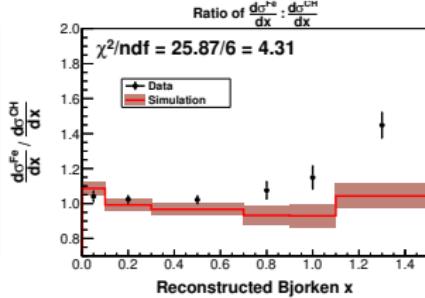
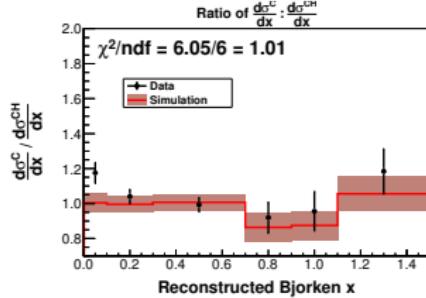
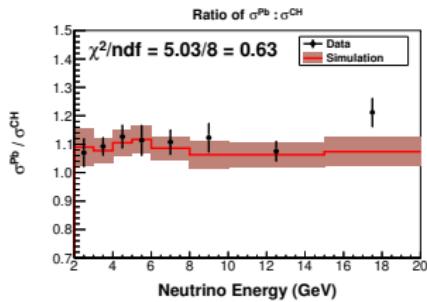
C/CH



Fe/CH



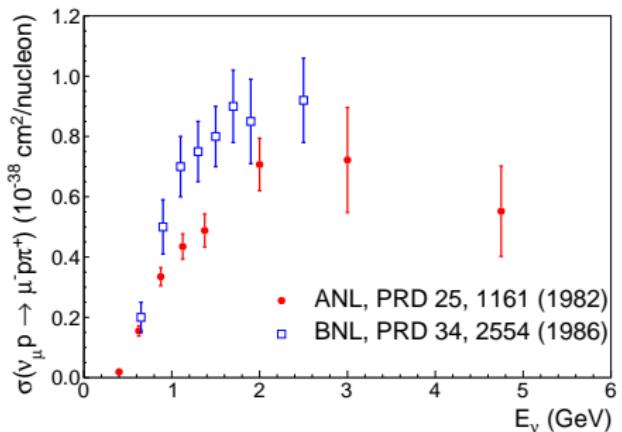
Pb/CH



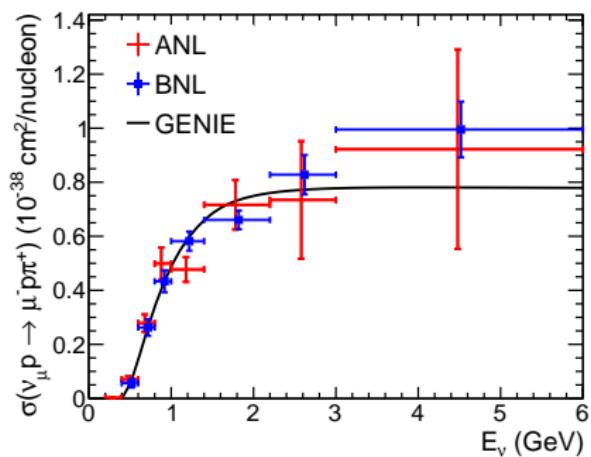
Increasing  $A$   $\longrightarrow$

# Resonant pion production on deuterium

Raw



Corrected



Right: C. Wilkinson, PR, et al, PRD 90, 112017

## T2K on-axis CC inclusive

